

## Millimeter- and Submillimeter-Wave Planar Varactor Sideband Generators

Haiyong Xu, Gerhard S. Schoenthal, Robert M. Weikle,  
Jeffrey L. Hesler, and Thomas W. Crowe

Department of Electrical and Computer Engineering  
University of Virginia  
Charlottesville VA 22903

**Abstract--** In this paper, the design and optimization of a varactor sideband generator (SBG) is presented. The integration of the diode with the embedding circuit enhances mechanical robustness and makes the circuits easy to handle compared with a whisker-contacted diode structure. A nonlinear analysis was used to determine the optimum varactor diode parameters for use at 600GHz, yielding an anode diameter of 1.8  $\mu\text{m}$  and an epitaxial layer doping of  $1 \times 10^{17} \text{ cm}^{-3}$ . A 200 GHz SBG is also implemented as a proof-of-principle. The measured results for 200 GHz are presented. The measured upper sideband conversion loss is 7-10dB over more than 20 GHz tuning range.

**Index Terms--** Conversion loss, epitaxial layer, millimeter- and submillimeter-wave sources, varactor sideband generator.

### I. INTRODUCTION

Millimeter- and submillimeter-wave sources can be used for a variety of applications ranging from molecular spectroscopy to wireless communications. However, there is a lack of frequency tunable sources at these wavelengths. A sideband generator (SBG) can be used to generate frequency tunable sidebands from a fixed source, and is therefore a commonly used device.

The best Schottky diode SBG in a corner cube mount gave 10.5  $\mu\text{W}$  of single sideband (SSB) output power with a conversion loss of 31 dB at 1.6 THz [1]. These results were improved dramatically with the application of varactor diodes as phase modulators. Two whisker-contacted varactor SBGs at 80 GHz and 1.6 THz were investigated by Kurtz [2], [3]. By switching to varactor diodes the conversion loss was improved to 14 dB at 1.6 THz. However, it has proved difficult to further develop these SBGs because of the difficulty in making the whisker-contact to the diode. This paper will describe a novel varactor-based SBG using planar diodes that overcomes the difficulties with previous designs. A proof-of-concept 200 GHz SBG is presented with measured results and a design of 600 GHz is discussed.

## II. BASIC THEORY AND SBG LAYOUT

For a SBG, it is most appropriate to use a low frequency to pump the diode due to the lack of power at high frequencies. A typical IF microwave source can easily fully pump the varactor and the LO signal will cause negligible capacitance modulation of the varactor. Better conversion loss can be achieved by this design [4]. Different IF pumping signals will lead to different conversion loss as described by Kurtz [3]. Ideally, the best achievable conversion loss, 3.94 dB, can be obtained using a bipolar square wave 180 phase modulation. The integrated varactor SBG circuit design is also based on this theoretical consideration. An open block photograph of the investigated SBG is shown in Fig. 1.

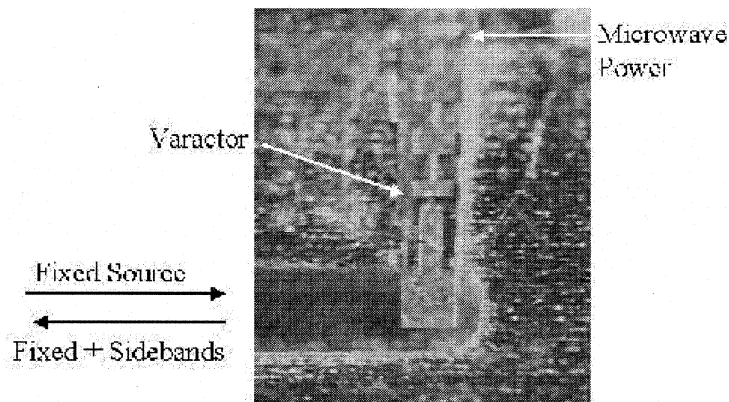


Fig. 1. Photograph of planar varactor circuit in SBG open block

The varactor and SBG circuitry are fabricated on a fused-quartz substrate, which is located in the microstrip channel. Waveguide-to-microstrip transitions are used to couple the high frequency signal from the waveguide and reflect its sidebands back to the waveguide. The microwave IF signal is applied to the varactor to control the LO signal phase shift. A low-pass microstrip filter is used to resonate the varactor and to block the LO signal.

## III. SBG DESIGN AND SIMULATION

The SBG equivalent circuit model is shown in Fig. 2. The planar Schottky varactor is modeled by a junction capacitance  $C_j$ , a series resistance  $R_s$ , a finger inductance  $L_{fg}$ , a finger to pad capacitance  $C_{fp}$  and pad to pad capacitance  $C_{pp}$ . The main design goal is to determine the varactor parameters and load impedance to realize LO signal 180 phase modulation.

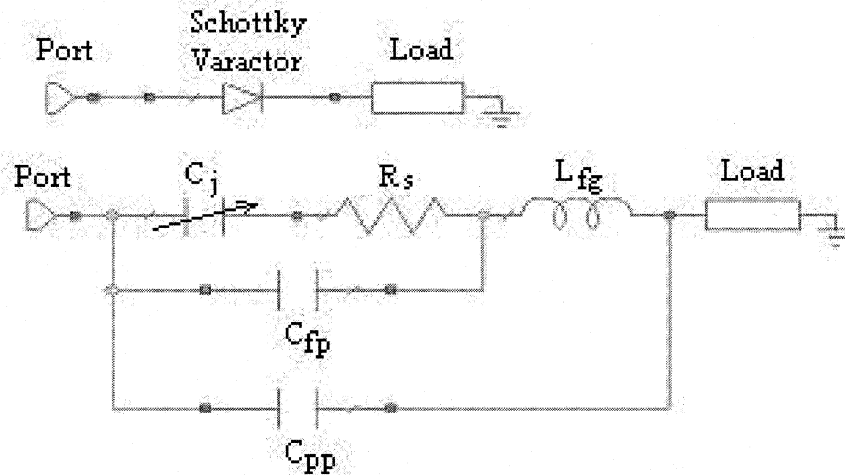


Fig. 2. Equivalent circuit of SBG

In order to achieve better phase modulation, the junction capacitance is initially set to resonate with the finger inductance at the LO frequency. The other varactor equivalent circuit parameters are first estimated based on previous simulations [5]. The  $L_{fg}$  and  $C_{j0}$  are optimized to give maximum phase shift for  $S_{11}$ . These values are translated into varactor dimension, such as anode size and finger length, according to typical formulas in [6]. The Ansoft High Frequency Structure Simulator (HFSS) is then applied to simulate the varactor integrated circuits. Coaxial ports were used at the anode junction, as described in [7]. Using this technique, all the varactor parasitic parameters including the filter circuit are analyzed in the HFSS. However, the nonlinear junction cannot be simulated since it changes with the pump. In order to include this nonlinear element, the three port S-parameter is exported into the microwave simulator package, Microwave Office, as a 3-port network.  $S_{11}$  is simulated again with the coaxial port terminated by a series junction resistor and capacitor, which is calculated based on anode size. This process is repeated to determine the varactor parameter, which will give a 180deg phase shift in reflection coefficient.

The 600 GHz Schottky varactor was optimized to have an epitaxial layer doping of  $1 \times 10^{17} \text{ cm}^{-3}$  and an anode diameter of  $1.8 \text{ } \mu\text{m}$ . The finger length is set to  $20 \text{ } \mu\text{m}$ . Since it is difficult to measure the S-parameters at 600 GHz, the 200GHz SBG was also designed to verify the theory. To make the fabrication simple, the same doping wafer is used. The anode size was chosen to be  $4.3 \text{ } \mu\text{m}$  with zero bias junction capacitance,  $C_{j0} \approx 15 \text{ fF}$ . The theoretical reflection coefficients with varactor bias voltage varying from  $-10 \text{ V}$  to  $0.5 \text{ V}$  are shown in Fig. 3. The predicted 200 GHz return loss is around 1dB, while the 600 GHz SBG is around 4 dB (with the microstrip and waveguide assumed lossless). The difference is due to the series resistance, which is determined by the anode size. The 200 GHz SBG junction

series resistance was calculated to be  $6 \Omega$ . The junction resistance for the 600 GHz SBG was calculated to be  $18 \Omega$ .

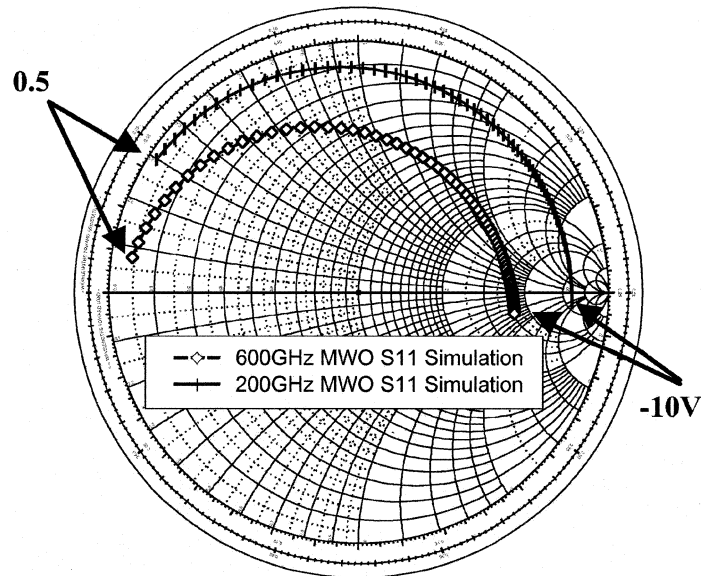


Fig. 3. SBG S<sub>11</sub> phase variation with sweeping of bias voltage

#### IV. FABRICATION AND MEASUREMENTS

The integrated circuits were fabricated in UVA Semiconductor Device Lab according to the simulation results. The SEM photo of 600 GHz varactor is shown in Fig. 4.

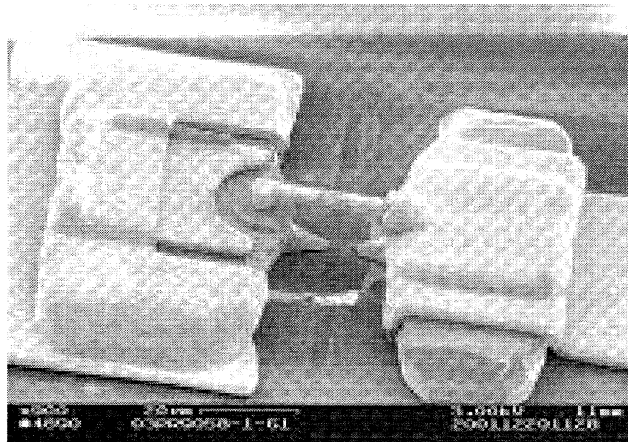


Fig. 4. SEM photo of 600 GHz SBG varactor structure

The varactor I-V curves and junction capacitances were measured, and were found to be similar to the simulation. The 200 GHz SBG blocks were first assembled and tested with

suitable circuits. The circuit S-parameters were measured with the Agilent 8510C Vector Network Analyzer (VNA) and an Oleson Microwave Lab WR-5 Extension (140-220 GHz). One of the reflection coefficients,  $S_{11}$ , corresponding to different varactor voltage biases was plotted in Fig. 5. The simulation result is also shown. The phase variation was nearly 180deg, which is quite similar to the design. However, the return loss is about 2 dB larger than the design. This increased loss is believed to be caused by dielectric and conductor losses, which are not considered in the simulation.

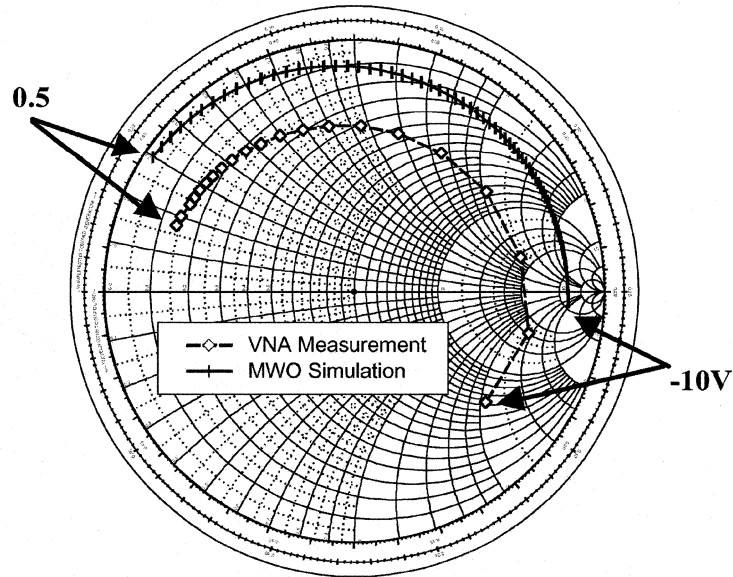


Fig. 5. Comparing  $S_{11}$  phase variation with different voltage bias

After the S-parameter measurement, the 200 GHz sideband generator conversion loss was tested. The test setup is shown in Fig. 6. It consists of WR-10 and WR-5 waveguides and components. A 100 GHz chain source is used to provide about 120 mW power. After a 100-200 GHz frequency doubler, the 200 GHz LO power is slightly more than 20 mW as measured by an Anritsu power meter. The WR-5 isolator is used to reduce the reflected signal effect. However, due to the large insertion loss of WR-5 isolator and WR-5 direction coupler, the SBG LO pump power at 200 GHz is about 1 mW. The modulating signal power is fixed at 15 dBm.

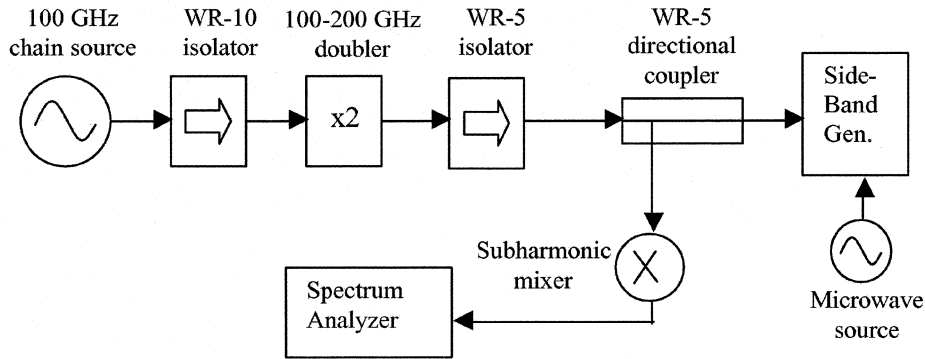


Fig. 6. The 200 GHz SBG conversion loss measurement setup

The reflected signals, LO and sidebands, are coupled into the coupling port of WR-5 directional coupler, and then sent to a 200 GHz subharmonic mixer RF port. The output IF signal from the mixer is sent to an Agilent 8565E spectrum analyzer. After calibrating out the mixer conversion loss and coupling loss, the SBG conversion loss is calculated, which is shown in Fig. 7. Over a 10 GHz frequency range, better than 10 dB conversion loss is achieved with 0 dBm input LO power.

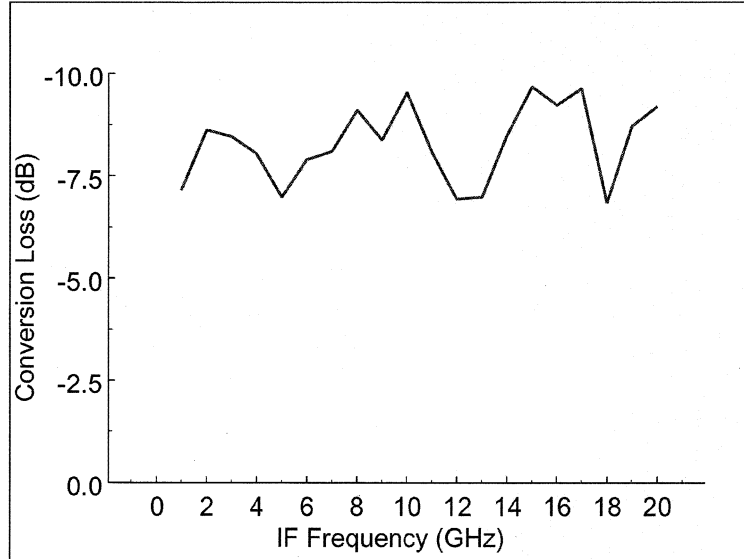


Fig.7. The test result of 200 GHz SBG conversion loss

## V. CONCLUSION AND DISCUSSION

In this paper, an integrated varactor SBG is investigated. The 200 GHz SBG is implemented and tested. The reflection coefficient simulation agrees well with the test results, which provides practical instructions for higher frequency SBGs. Higher LO power, 10 mW, was also applied to the 200 GHz SBG. The upper sideband output power is about 1 mW, which indicates 10 dB conversion loss. The 600 GHz SBG will be tested using a solid state source and laser source. It's also expected that this SBG can be scaled to THz frequencies to provide a high power tunable source.

## ACKNOWLEDGMENT

This research was supported by the US Army N.G.I.C. contract DASC01-01-C-0009.

## REFERENCES

- [1] E. R. Mueller and J. Waldman, "Power and Spatial Mode Measurements of Sideband Generated, Spatially Filtered, Submillimeter Radiation," *IEEE Trans. Microwave Theory Tech.*, vol. 42, No. 10, pp. 1891-1895, Oct. 1994.
- [2] D. S. Kurtz, J. L. Hesler, T. W. Crowe and R. M. Weikle, "Millimeter- Wave Sideband Generation Using Varactor Phase Modulators," *IEEE Microwave and Guided Wave Letter*, vol. 10, No. 6, pp. 245-247, June 2000.
- [3] D. S. Kurtz, "Sideband Generation for Submillimeter Wave Applications," Ph.D. Dissertation, Univ. of Virginia, May, 2000.
- [4] P. S. Henry, "An Efficient Microstrip Upconverter for  $K_a$  Band," *IEEE MTT-S International Microwave Digest of Technical*, pp. 137-139, 1975.
- [5] J. L. Hesler, "Planar Schottky Diodes in Sub-millimeter Wavelength Waveguide Receivers", Ph.D. Dissertation, Univ. of Virginia, January, 1996.
- [6] R. F. Pierret, *Semiconductor Device Fundamentals*. Purdue University: Addison-wesley Publishing Company, 1996.
- [7] J. L. Hesler, W. R. Hall, T. W. Crowe, R. M. Weikle, B. S. Deaver, Jr., R. F. Bradley and S. K. Pan, "Fixed-Tuned Submillimeter Wavelength Waveguide Mixers Using Planar Schottky Barrier Diodes," *IEEE Trans. Microwave Theory Tech.*, vol. 45, No. 5, pp. 653-658, May 1997.

